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The Evaluation of Structure – Property Relationships in the Dual Matrix Ductile Iron by Magnetic Barkhausen Noise Analysis

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Abstract

Structure-property relationships in ferritic ductile iron with a dual-matrix (ferrite, martensite) structure were evaluated by Magnetic Barkhausen Noise (MBN) analysis. Specimens were partially austenitised in the ferrite-austenite region at 795°C and 815°C for 20 minutes, and then quenched in 100ºC-oil to obtain different phase contents. The specimens were subjected to tempering at 500ºC for 1 and 3 h. The results showed that the volume fraction of phases can be controlled to modify the mechanical properties, and any change in the microstructure can be monitored by MBN.

Keywords: Dual-matrix ductile iron, Microstructure, Magnetic Barkhausen Noise.

1 Introduction

The mechanical properties of ductile irons are controlled by the volume fracture and distribution of matrix phases and microstructures. In the newly developed ductile cast iron with dual matrix structure, the structure consists of ferrite, and martensite or ausferrite (bainitic ferrite and high carbon austenite), which is called Dual Matrix Structure (DMS) [1-7]. This new material meets requirements for good toughness and higher ductility in some automobile components. The tensile and proof strengths of ductile iron with DMS are much higher than pearlitic and ferritic grades, and ductility is slightly lower than ferritic grades. The tensile strength and ductility can satisfactorily be optimized by the critical combination of austenitizing and tempering time and proeutectoid-ferrite volume fraction (PFVF) or martensite volume fraction (MVF) [8-18].

Under the effect of an external magnetic field, ferromagnetic materials tend to become magnetized through the reorganization of the existing micromagnetic structure that consists of randomly distributed magnetic domains. The neighbor domains have an interface named as domain wall (Bloch wall). Magnetic Barkhausen Noise (MBN) signals represent the irreversible creations and motions of domain walls. Therefore, the characteristics of MBN are strongly dependent upon the nucleation and motions of the domain walls. Domain wall nucleation becomes more difficult when the grain size increases; the pinning sites in the microstructure such as precipitates, dislocation tangles, grain boundaries require higher magnetic fields for domain wall motion; any distortion in the crystalline structure makes the reorganization of the domain structure harder; and the existence of the non magnetic phases in the microstructure, causes internal demagnetizing fields opposing the external magnetic field; applied stresses or residual stress state may also affect the MBN [20-27]. There is limited information concerning the MBN analysis of ductile irons [13,24]. The purpose of this study is to non-destructively quantify the volume fraction of phases, and to evaluate structure-property relationships in the dual matrix ductile irons by MBN.

2 Experimental procedure

The ferritic ductile iron (Table 1) was produced in an induction furnace. A 250 kg molten iron with 6-7 % Mg containing ferrosilicon alloy was treated at 1450ºC by the tundish cover ladle method. Inoculation was carried out with % 75 ferrosilicon alloy. The melt at 1400-1450ºC was cast into Y-block sand moulds in accordance with ISO 1083. 10mmx10mmx5mm samples were machined from lower portion of the block. Specimens were austenitised for 20 minutes at 795°C, and 815°C which correspond to formation of approximately 25 vol.% and 62 vol.% martensite [10]. Then, they were quenched into an oil-bath at 100°C. Another group was prepared by applying the conventional heat treatment (full-austenitization at 900°C/20 minute), and then, oil quenching to the as-cast specimens.

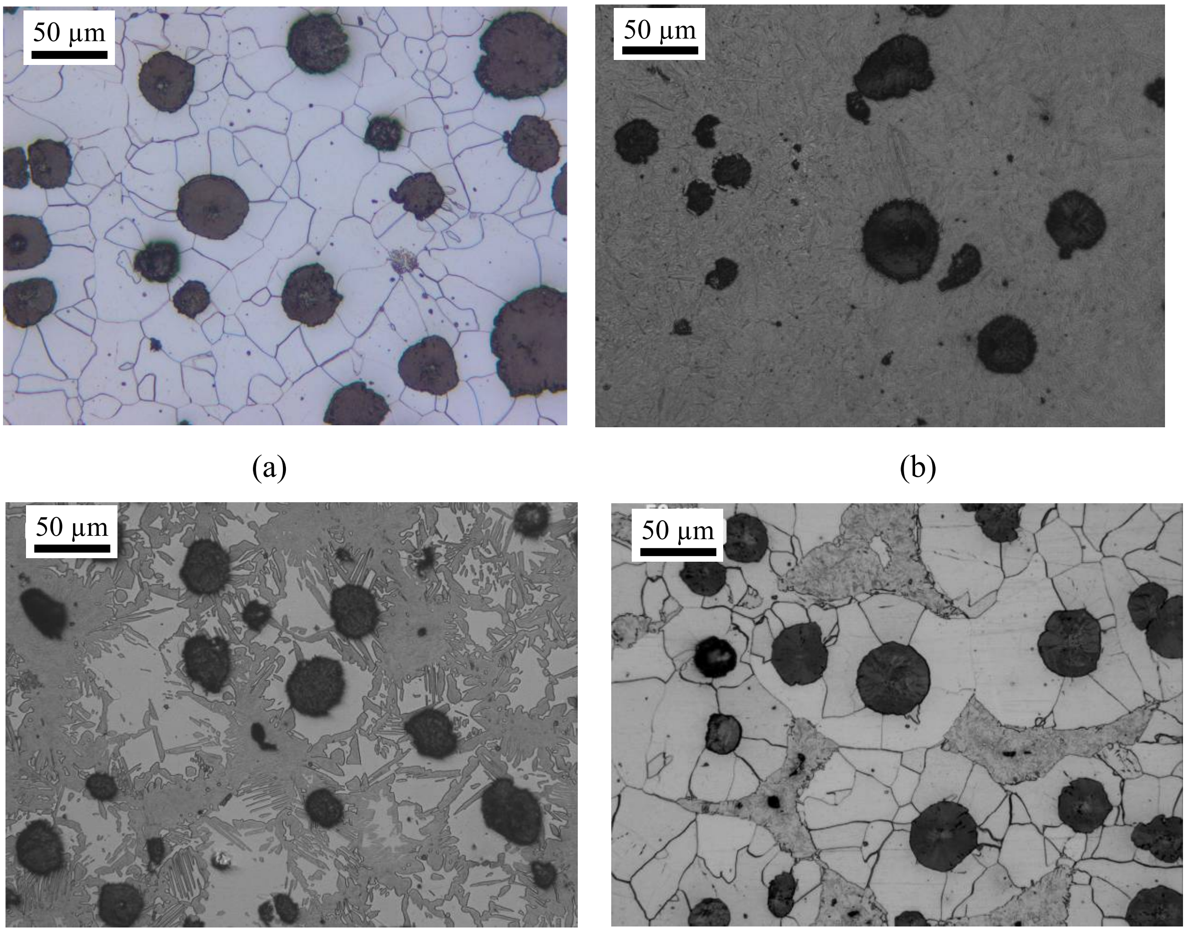
Table 1. Chemical composition of the ductile iron used (wt %).

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Ti	Mg	Fe
3.50	2.63	0.318	0.019	0.009	0.031	0.042	0.042	0.003	0.055	<0.012	0.047	Rest

The proportions of the constituents were determined by point counting on 2% nital etched metallographic sections. Between 1000 and 2000 points were counted to keep the standard error of the volume fraction of phases below 6%. Standard tension tests of the specimens machined from the bottom section of the Y-block were carried out using a DARTEC machine. At least five specimens were tested for each heat treatment condition, and average values were calculated. MBN measurements were carried out using Stress Tech µscan 500-2. A cyclic magnetic field of 125 Hz was induced in a small volume of the specimen with a coil. The signal amplification and the gain were adjusted properly to obtain a smooth sine-waveform of magnetic excitation. Two parameters from the data collected were analyzed: the maximum amplitude (relative r.m.s. voltage) and the position (relative magnetic excitation field) of the MBN peak. The r.m.s. voltage is a function of the jump size of domain walls, and the corresponding relative magnetic excitation field represents the magnetic field strength required for the movement of the domain walls from pinning sites.

3 Results and discussion

The microstructure of the as-cast specimen consists of ferrite grains surrounding the graphite nodules (Fig. 2.a). Oil-quenching of the fully austenitised sample resulted in a complete martensitic matrix (Fig. 2.b). On heating the specimens to 795°C or 815°C, austenite nucleates at grain boundaries which are located in the eutectic cell boundaries, and then, grows into the ferrite to achieve an equilibrium volume fraction. Oil-quenching of these samples produced dual-matrix structures (Fig. 2.c and 2d) having different martensite volume fractions (MVF).



(a) (b) (c) (d)

Figure 2. Micrographs demonstrating the microstructures. (a) as-cast, (b) oil quenched from 900°C, (c) oil quenched from 815°C, (d) oil quenched from 795°C

Ferritic as-cast sample exhibited the highest ductility and the lowest strength. The conventionally heat treated sample, having martensitic structure, has the highest proof strength (PS) and tensile strength (UTS), and the lowest ductility. In the samples quenched from ICAT range, as austenitising temperature increased, in parallel to the increase in MVF, PS and UTS increased, but total elongation decreased. In the specimens with lower PFVF, in which ferrite around graphite nodules was completely surrounded by martensite (Fig. 2.c), the martensite structure may restrict deformation of a larger fraction of the total volume of the low strength ferrite under tensile loading and ductility decreases with increasing continuity of martensite along eutectic cell boundaries. % total elongation of the 795 specimen was superior to that of the specimen with completely martensite matrix. Increasing the tempering duration up to 3h increases the total elongation percentage. The specimen 815T3 having 49 vol.% MVF exhibited the best combination of strength and ductility.

Ferrite is easily magnetised/demagnetised, and has a strong MBN activity located at a low magnetic field whereas martensite, which is highly resistant to demagnetization, shows a low MBN emission located at a high field [24-26, 28]. Since MBN contains collective jumps of domain walls, the jump size will directly affect the associated voltage change. Therefore, high MBN peak amplitude indicates that there is a wider range of jump sizes in the as-cast sample than those in the fully martensitic and dual-matrix samples. Thus, a decrease in the MBN peak height together with an increase in the relative magnetic excitation field can be considered as an evidence for the increase in martensite content. There is a clear relationship between MBN emission and austenitising temperature (Fig. 3).

Table 2. Results of metallographic investigations and tension tests

Specimen	Martensite vol. %	Proeutectoid-Ferrite vol. %	0.2% Proof Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation (%)
As-cast	-	90	262	465	27.7
795			353	578	9.2
795T1	24.7	65	261	467	21.7
795T3			239	395	17
815			411	601	6.3
815T1	61.8	28	368	670	10.9
815T3			362	580	13.2
Q900			1121	1341	1.2
Q900T1	89.9	-	933	1227	2.1
Q900T3			900	1097	2.4

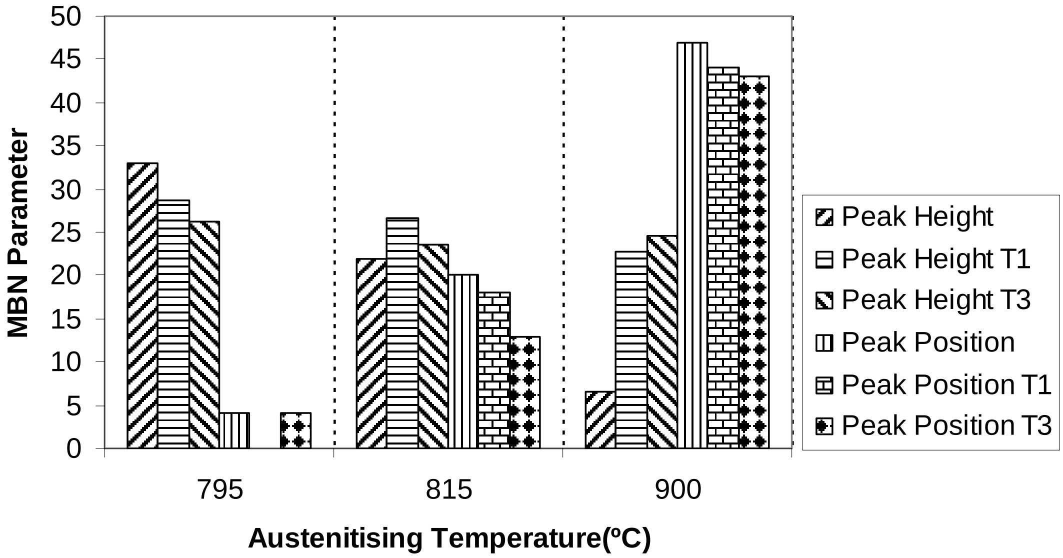


Figure 3. Effect of tempering at 500°C for 1h (T1) and 3h (T3) on MBN parameter with respect to the austenitising temperature (Peak position of 795T1 is zero).

For the martensitic samples quenched from 900°C, the peak amplitude increased with increasing tempering time at 500°C. In parallel to the increased duration of tempering, the low amplitude broad peak of as-quenched martensite transformed into high amplitude narrow peaks situated at a lower magnetic field. Small martensite needles cause very small domains and the relative volume occupied by a domain wall is the largest. The resistance to the domain growth is very high since the domain walls are pinned due to high dislocation density of martensite laths. The reversal of magnetization requires a strong field, displacements of the domain walls are short, and it is difficult to create new walls. The morphological change to spheroidal cementite due to tempering increased the MBN peak signal by affecting the domain wall size and domain nucleation.

Fig. 4 shows that both 0.2% proof and tensile strengths decrease as PFVF increases; and this change can be monitored by increase in the MBN peak height, and a shift in the MBN peak position. Similarly there is a good correlation between % total elongation and MBN peak height (Fig. 5).

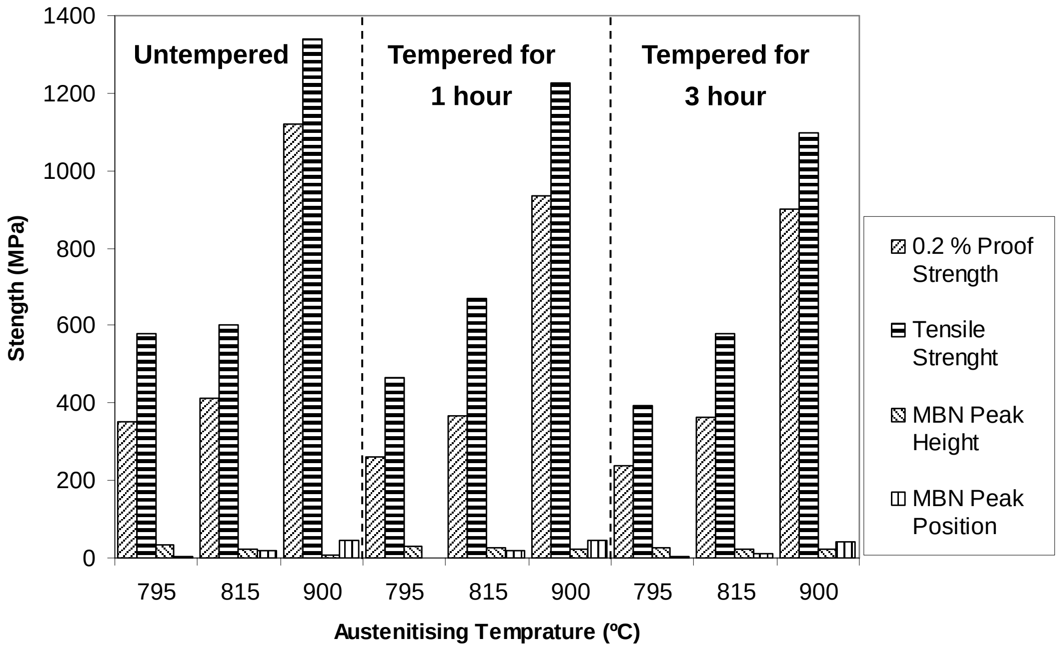


Figure 4. Variation of MBN parameters and strength of all samples with the austenitising temperature (Peak position of 795T1 is zero).

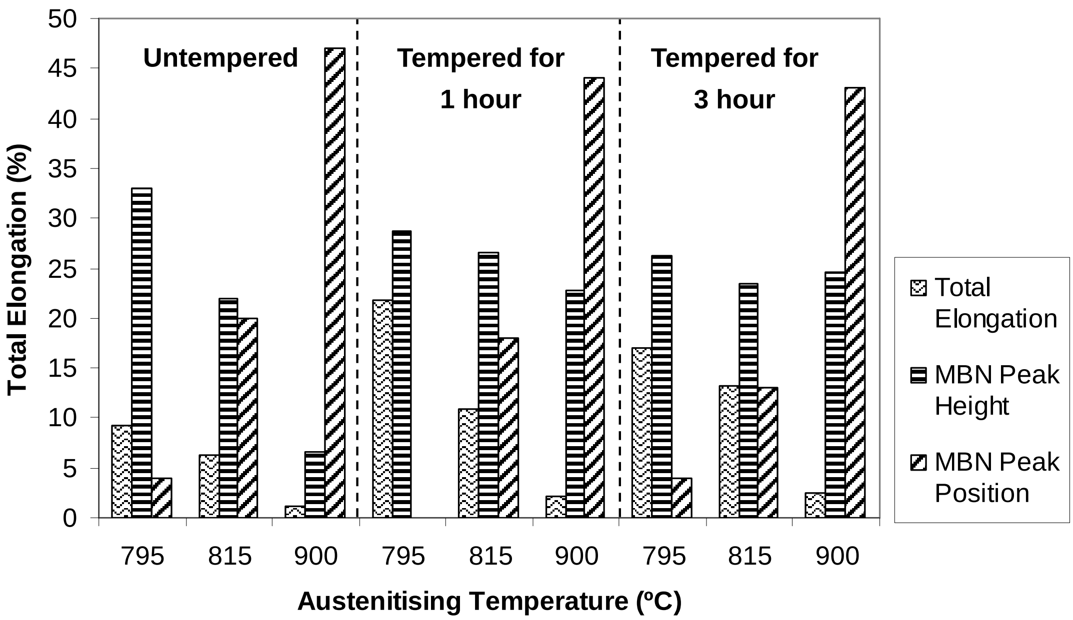


Figure 5. Variation of MBN parameters and total elongation of all samples with the austenitising temperature (Peak position of 795T1 is zero).

4 Conclusion

Obtaining the dual-matrix microstructure by intercritical austenitising and oil-quenching of ductile iron has an advantage of precise control of martensite and pro-eutectoid ferrite volume fractions. For an appropriate combination of intercritical annealing, quenching and tempering, the strength and ductility can be optimized. By measuring the MBN fingerprint, i.e., the height and the position of MBN peak, the changes in the microstructure of dual-matrix ductile irons, and corresponding variations in proof and tensile strengths, and total elongation can be estimated non-destructively.

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